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Spatiotemporal variability underlying skill in curved-path walking☆

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ABSTRACT

Background: Daily life walking frequently involves curved paths. While mean gait characteristics and orientation of the body during curved path walking have been described, little has been reported about spatiotemporal variability during curved path walking and its relation to the motor skill of walking in older adults.

Research question: Among community-dwelling older adults, is greater spatiotemporal variability during curved path walking related to better curved path walking ability?

Methods: Community dwelling older adults (n = 34) completed the Figure-of-8 Walk Test (F8W, a measure of curved path walking ability) and usual straight path walking on an instrumented walkway. Standard deviations for step length, stride width and step time (step length variability, SLV, stride width variability, SWV, step time variability, STV) during both conditions were determined, along with time and number of steps to complete F8W. Associations were examined with Pearson r correlation coefficients, regressions determined contributions of variability during curved path walking to F8W performance, and AUC analyses were used to determine the ability of variability during curved path walking to distinguish better vs poorer F8W performance.

Results: F8W time and steps were negatively associated with both SLV (r's = −0.37, $p < 0.05$) and SWV (r's = −0.67 to −0.82, $p < 0.001$). Both SLV and SWV independently contributed to F8W performance (SLV βs = −0.26 to −0.29, $p < 0.03$; SWV βs = −0.74 to −0.76, $p < 0.001$). The AUC of the ROC curve for SLV was 0.716, and for SWV was 0.765.

Significance: Greater spatial variability, particularly SWV, was associated with better motor skill of curved path walking. It is important for clinicians to understand the variables that contribute to successful performance of complex walking tasks as these can be targets for rehabilitation. The findings suggest that practice of adjustment of stride width and step length during walking are important.

1. Introduction

Walking is a highly skilled motor behavior. A motor skill in that adult human walking developed through a process of motor learning and practice. As a result of this process, mature human walking is a smooth translation of the body, with a stepping pattern that is essentially automatic, reproducible and integrated with postures and phases of gait, adaptive to changes in condition and efficient in performance [1–3]. It is because of this high degree of consistency in the stepping pattern of walking that greater gait variability during usual straight-path walking has been known to be an early indicator of mobility impairment, and associated with falls, incident mobility disability, and central nervous dysfunction [4–6].

While the consistency of the stepping pattern is characteristic of the motor skill of usual walking over straight paths, the adaptability of the stepping pattern of walking is necessary for effective and efficient performance over curved paths. As the center of pressure shifts toward the limb on the inside, shortened step lengths of the inside limb and lengthened steps of the outside limb enable the curved path to be managed effectively with little disruption of the rhythm of walking [7,8]. As such, the ability to adapt step lengths and widths, or greater variability of the spatial characteristics of stepping, may be essential aspects of highly motor skilled behavior in curved path walking. While mean gait characteristics and orientation of the body (e.g. center of mass, trunk and lower limb trajectories) of curved path walking have been described [7–9], little has been reported about the variability of stepping in curved path walking and the relation to the motor skill of walking.

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Among older adults, a measure of curved path walking ability, the Figure-of-8 Walk has been an indicator of the motor skill in walking beyond walking speed alone [10].Using the Figure-of-8Walk test, we examined the variability of stepping (step length, SLV, stride width, SWV, step time variability, STV) during curved path walking in healthy community dwelling older adults. Given the necessity for path adjustments about the curves with direction changes, we expected: 1) greater spatial variability during curved path walking to be related to better curved path walking ability, 2) greater spatial variability will distinguish those with good motor skill of walking, and 3) stronger associations between curved path walking ability and spatial variability compared to temporal variability, as we expect less variation in rhythm in these healthy older adults.

2. Methods

2.1. Participants

Community-dwelling older adults (n = 34) were recruited during two local senior health fairs to participate in a study examining the associations between executive function and performance on complex walking tasks including obstacle negotiation, backward walking, and curved path walking. These data were a secondary analysis of the larger data set. Inclusion criteria: 50–90 years of age and ambulatory indoors without assistance. Exclusion criteria (determined by participant self-report): 1) pain limiting walking ability, 2) a diagnosed neurological disorder, such as Parkinson's disease, Multiple Sclerosis or stroke, 3) an amputation or fused lower extremity joint, 4) hospitalization in the last 6 months for major surgery, 5) dyspnea at rest or with activity, or 6) diabetes not well controlled. The study was approved by the university's institutional review board.

2.2. Gait measures

2.2.1. Curved path walking: Figure-of-8 Walk Test (F8W)

The F8W was used as the measure of curved-path walking. The F8W time and steps have demonstrated interrater (ICC = 0.90; ICC = 0.92, respectively) and test-retest reliability (ICC = 0.84; ICC = 0.82, respectively) in older adults with mobility disability [10] and in persons with chronic stroke (inter-rater reliability, ICC = 0.966–0.999; test-retest reliability, ICC = 0.977–0.978) [11]. Concurrent validity established as a measure of the motor skill by relation of F8W time to step length coefficient of variation (COV), r = 0.279, F8W time and steps with step width COV, r = −0.277 and 0.339 [10], and construct validity for motor skill by relation of F8W time and steps to executive cognitive function, DSST and Trails B (time, r = -0.308 and 0.336; steps, r = −0.201 and 0.261) [12], all, $p < 0.05$. Impaired motor skill has previously been defined as ≥8 s to complete the test [13,14]. Full procedures for the F8W were previously described [10]. Briefly, participants walked on an instrumented walkway (Protokinetics, Inc.[a]) starting midway between 2 cones positioned 5 feet apart and completed a figure-of-8 path around the cones at their usual pace. Time and number of steps to complete the F8W were recorded. Faster times and fewer steps indicate better performance. Gait variability was determined for curved-path walking (F8W) using the instrumented walkway data. Variability was the standard deviations of step length, stride width, and step time derived from all footfalls during the F8W. Spatial variability parameters were defined using methods for nonlinear walking [15].

2.2.2. Usual straight path walking: gait speed and gait variability

Participants walked at their self-selected comfortable pace across 4-m of instrumented walkway (Protokinetics, Inc.[1]) with 2-m of non-instrumented path at each end for acceleration/deceleration. Usual gait speed was determined as the mean of 4 trials. Variability was the standard deviations of step length, stride width, and step time derived from all footfalls recorded on the walkway during one trial, then averaged across 4 trials. As gait variability has been used as an indicator of the neuromotor control of straight-path walking, [16,17] and has predictive ability for falls independent of gait speed [4], we used variability during straight path walking as a measure of baseline neuromotor control.

2.3. Participant characteristics

Self-reported age and cognitive function were recorded. Cognitive function was defined using the Montreal Cognitive Assessment (MoCA). The MoCA is a cognitive screen for mild cognitive dysfunction. Specifically, the MoCA is used to evaluate executive and visuospatial function, memory, language, conceptual thinking, calculations, and orientation [18]. It has demonstrated test-retest reliability (r = 0.92, $p < 0.001$), internal consistency, Cronbach alpha, 0.83, and validity for detection of Alzheimer's disease and mild cognitive impairment in older adults, sensitivity, 100%/ and 90% respectively, specificity, 87% [19]. The MoCA was administered by a trained experimenter. The MoCA has a possible score of 30 points, with a score of 26 or higher considered normal.

2.4. Data analyses

Pearson *r* correlations were used to examine associations among spatiotemporal variability of curved path walking and F8W time and steps. To assess the contributions of gait variability to the motor skill of walking, a series of regression analyses were used with the measures of F8W performance (time and steps) as the dependent variables. In Model 1, we accounted for the variance in curved path walking skill explained by age, and mean F8W spatiotemporal parameters (mean step length, width and step time). In Models 2–4, SLV, SWV and STV were individually added to Model 1 to determine the additional variance in curved path walking skill explained by each type of variability. In addition to accounting for age, in Models 2–4 we also accounted for baseline neuromotor control (i.e. SLV, SWV, or STV during usual straight-path walking). As the study is secondary analysis of data in an existing dataset, sample power was not determined in an a priori power analyses. In light of potential inadequate power for some analyses (i.e. regressions), the findings should be considered exploratory.

To determine the ability of variability during curved path walking to classify motor skill in walking (F8W greater or less than 8 s), we calculated sensitivity and specificity for each component of variability using established methods [20]. We created receiver operating characteristic (ROC) curves, where sensitivity was plotted on the y-axis and the false positive rate (1-specificity) was plotted on the x-axis. The area under the curve (AUC) was determined for each variability measure to produce a comparison of the accuracy of the measures to classify motor skill in walking. Data analysis was carried out with SPSS version 22 (SPSS Inc, Chicago, IL.).

3. Results

3.1. Participant characteristics

The participants were generally young-old, the majority female, and with generally age-related normal cognitive function (Table 1) [19,21]. The average usual straight-path gait speed was 1.18 m/s, which is similar or better than previous reports for community dwelling older adults free from dementia and disability [22,23]. The variability during straight-path walking was also similar to values previously reported for community dwelling adults [22]. Using the F8W cut-off score of 8 s to define the motor skill of walking, 50% (n = 17) completed the F8W in ≤ 8 s, indicative of good motor skill of walking.

[1] **Suppliers:** ProtoKinetics LLC, 60 Garlor Drive, Havertown, PA 19083 USA.

Table 1
Demographics and walking variables, group mean, SD and range (n = 34).

Characteristics	Mean	SD	(Range)
Sex, # of men	11		
Age, *yrs*	70.85	9.18	(54-90)
MoCA, *0-30*	26.71	2.61	(20-30)
Usual straight-path walking			
Usual velocity, *m/s*	1.18	0.19	(0.73-1.62)
Mean SL, *cm*	65.77	7.84	(50.73-79.38)
Mean SW, *cm*	8.66	2.63	(3.32-14.32)
Mean ST, *s*	0.56	0.05	(0.48-0.70)
SLV, *cm*	2.70	0.66	(1.60-3.84)
SWV, *cm*	2.36	0.74	(0.56-3.78)
STV, *s*	0.02	0.006	(0.01-0.04)
Curved-path walking (F8W)			
Number of steps	14.2	1.97	(11-19)
F8W time, *s*	8.28	1.77	(5.41-13.59)
Mean SL, *cm*	38.82	6.01	(26.55-57.75)
Mean SW, *cm*	11.41	3.28	(5.85-13.60)
Mean ST, *s*	0.59	0.07	(0.47-0.80)
SLV, *cm*	20.24	4.98	(10.54-31.52)
SWV, *cm*	20.82	4.81	(10.38-28.64)
STV, *s*	0.04	0.02	(0.01-0.10)

MoCA = Montreal-Cognitive Assessment; SL = step length; SW = stride width; ST = step time; SLV = step length variability; SWV = stride width variability; STV = step time variability; F8W = Figure-of-8 Walk Test.

3.2. Associations between spatiotemporal variability during curved-path walking and the motor skill of curved path walking (F8W time and steps)

F8W time and steps were negatively associated with both SLV and SWV (time, $r = -0.372$, $p = 0.03$; $r = -0.677$, $p < 0.001$, respectively; steps, $r = -0.373$, $p = 0.03$; $r = -0.823$, $p < 0.001$, respectively), but not with STV (time $r = 0.303$, $p = 0.081$; steps $r = 0.208$, $p = 0.239$).

3.3. Contribution of spatiotemporal variability to the motor skill of curved path walking (F8W time and steps)

Mean spatiotemporal variables explained 57% of the variance in F8W time and 44% of variance in F8W steps (Table 2). The inclusion of SLV in the model explained an additional 6% of the variance for F8W time (F change, $p = 0.028$) and an additional 8% of the variance for F8W steps (F change, $p = 0.028$). The inclusion of SWV in the model explained an additional 24% of the variance for F8W time (F change, $p < 0.001$) and an additional 25% of the variance for F8W steps (F change, $p < 0.001$). No additional variance was explained by the inclusion of STV to the model for either F8W time or steps (F change, $p > 0.40$).

3.4. Distinguishing the motor skill of walking using spatial variability during curved-path walking

Based on the area under the curve derived from the ROC curves, both SLV and SWV distinguished between high and low levels of motor skill of walking. The AUC of the ROC curve for SLV was 0.716 with a confidence interval of 0.541 – 0.892. Step length variability during curved-path walking had an optimum cut-off value to distinguish high from low motor skill of walking, of 19.85 cm with 71% sensitivity and 71% specificity (Fig. 1A). The AUC of the ROC curve for SWV was 0.765 with a confidence interval of 0.598–0.932. Stride width variability during curved-path walking had an optimum cut-off value to distinguish high from low motor skill of walking, of 20.33 cm with 77% sensitivity and 65% specificity (Fig. 1B). Step time variability was not examined due to nonsignificant associations with, and contributions to F8W time and steps.

4. Discussion

In this study of the contribution of spatiotemporal variability to the motor skill of curved path walking, the findings supported our expectations. Greater spatial variability was associated with better curved-path walking ability, and both SLV and SWV had unique contributions to curved path walking ability. Additionally, spatial variability during curved path walking distinguished those older adults with better motor skill of walking. Temporal variability was marginally or not associated with curved path walking ability, and the marginal relation observed was opposite the directional association with spatial variability (e.g. the lesser the temporal variability the better the curved path walking ability).

During usual straight path walking, greater gait variability indicates poorer walking performance and lesser motor skill [10,24,25]. The

Table 2
Linear regression model summary for the variance in the motor skill of curved path walking explained by spatiotemporal variability.

Independent variables	F8W time to complete β (*p*)	F8W number of steps β (*p*)	F8W time to complete Adjusted R square	F8W number of steps Adjusted R square
Model 1: Variance explained by mean F8W variables			0.571	0.436
Mean step length	−0.374 (0.095)	−0.555 (0.034)		
Mean stride width	−0.057 (0.638)	0.010 (0.940)		
Mean step time	0.497 (0.001)	0.048 (0.743)		
Model 2: Additional variance explained by step length variability			0.639	0.531
Mean step length	−0.516(0.008)	−0.645 (0.004)		
Mean stride width	−0.012 (0.918)	0.057 (0.661)		
Mean step time	0.510 (< 0.001)	0.033 (0.794)		
SD, step length	−0.258 (0.028)	−0.293 (0.028)		
Model 3: Additional variance explained by stride width variability			0.797	0.687
Mean step length	0.097 (0.568)	−0.012 (0.956)		
Mean stride width	0.091 (0.306)	0.167 (0.135)		
Mean step time	0.611 (< 0.001)	0.138 (0.200)		
SD, stride width	−0.737(< 0.001)	−0.758 (< 0.001)		
Model 3b: Additional variance explained by step time variability			0.564	0.425
Mean step length	−0.376 (0.097)	−0.557 (0.035)		
Mean stride width	−0.054 (0.660)	0.014 (0.921)		
Mean step time	0.522 (0.001)	0.075 (0.627)		
SD, step time	−0.100 (0.463)	−0.105 (0.503)		

β, standardized coefficients.
All models adjusted for age and baseline neuromotor control. Model 1 was adjusted for step time variability, other gait variability measures made similar but less adjustments to the R square of Model 1 (data not shown). Models 2–4 were adjusted for the matched type of variability during usual straight-path walking.

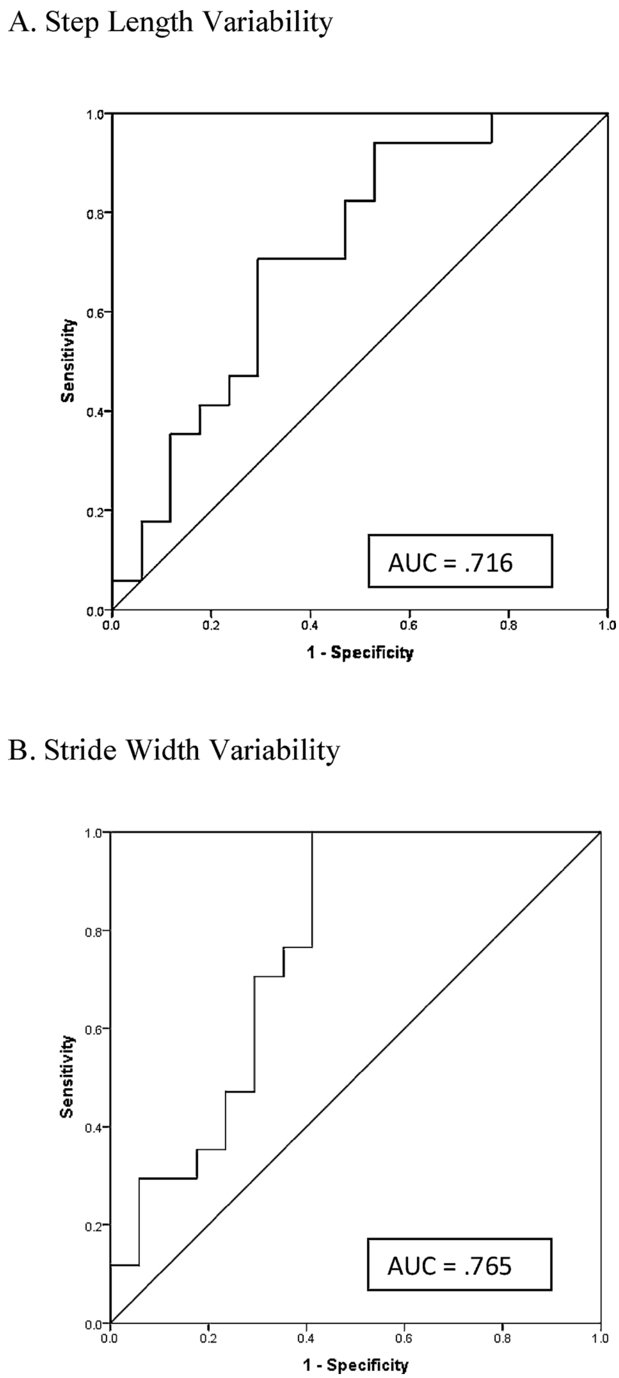

Fig. 1. Receiver operating characteristics (ROC) curve for step length variability (A) and stride width variability (B). The curved line is the ROC curve. The straight line indicates non-discriminating characteristics of the test. AUC = Area under the curve.

findings of greater spatial variability associated with better motor skill of walking (i.e. negative correlations of SLV and SWV with F8W time and steps) contradicts this conventional wisdom. From observations and based on prior research [7,8,26], the ability to vary step length and stride width enables both smooth continuity of the center of pressure path and energy efficient navigation of curves. Thus, for curved path walking, greater spatial variability represents the automatic adaptability of the stepping pattern for effective and efficient performance.

While both SLV and SWV contributed to motor skill of curved-path walking, SWV emerged as the stronger contributor. This was illustrated both by the stronger associations between SWV and F8W performance (r's = −0.68 to −0.82, vs. SLV r's = −37), and by the amount of added variance in F8W explained by SWV. During usual straight path walking, older adults walking at near normal gait speeds and no history of falls exhibited a moderate amount of step width variability, while those who reported falling exhibited too much or too little step width variability [27]. The tolerance for a moderate amount of step (stride) width variability in usual walking may represent a natural dependence for online adaptability to environmental demands. This adaptation, or exploration strategy during usual walking may then more easily allow for further exploitation of SWV to fit task demands during complex walking tasks.

In healthy younger adults, the stride at the apex of the curve is characterized by increased stance time on the inner leg, a shift of the center of mass towards the inner side, and increased step length and swing velocity of the outer leg [7,8]. Such stride adaptations present a substantial challenge to mediolateral balance control. In a previous study examining age-related differences in gait strategies during adaptive walking, compared to young adults, healthy older adults maintained mediolateral walking smoothness but adopted a general motor strategy of reduced step length and increased SWV during different challenging walking tasks [28]. In the current study, it is notable that mean step length was markedly reduced during F8W. Older adults may have responded to the challenge of the F8W by adopting a similar motor strategy (average step length was shortened during F8W, SWV increased) throughout the entire path, not just on the curves. This strategy may promote adaptability and mediolateral control.

Because of the lack of significant association of step time variability and curved path walking, it is difficult to comment with any confidence on the relation or the difference in the direction of the association with temporal compared to the spatial variability. In relation to the lack of association or an interpretable association, some potential explanations might be: 1) among the healthy adults studied, curved path walking induced little to no change in the rhythmicity of their usual straight path walking; 2) as secondary data analysis the study was underpowered to detect a significant difference given the limited range of temporal variability demonstrated; or 3) the adjustments demonstrated in spatial variability accommodated walking to manage the curved path, thereby preserving walking rhythmicity during curve negotiation. In young adults there were differences in the amount of time spent in stance and swing phases between straight-path walking and curved path walking; however, the overall stride duration was the same, indicating no loss of rhythmicity from straight to curved path walking [8]. In our healthy sample, the average step time variability during straight path walking was low, and remained generally low during F8W. Therefore, while it may be possible that the study is underpowered to detect an association of the temporal variability with curved path walking, it is also possible that among the older adults in good health studied, the range of temporal variability during curved path walking was too limited to define an association.

5. Limitations

A limitation of this study was the calculation of F8W variability from a single trial (ranging from 11 to 19 steps). Our decision was to be consistent with the methodology (single trial) on which the psychometric properties for the F8W are based [10]. Multiple trials would have induced a practice effect and we were interested in differences in performance with first exposure to the task.

6. Conclusion

Older adults with better motor skill of walking exhibited greater spatial variability when it's beneficial to do so for improved task success. Understanding the control that underlies good performance allows clinicians to target these variables during rehabilitation. Based on the data, we suggest that practice of active adjustment of stride width and step length during walking are important. As curved-paths are a frequent component of daily walking both in the home and community (rounding furniture, stair landings, other people), it is essential that rehabilitation professionals understand the critical components of effective performance, and address these components in the design and implementation of interventions to improve the motor skill of walking. Future research directions include a comparison of young and older adult performance on the F8W test to explore age-related strategies. This exploration of age-related strategies would help define an optimal level or range of variability appropriate for complex walking tasks, and the combination of types of variability that result in the best or worst performance – the aim, effective and efficient walking. Additionally, exploring the use of rhythmic auditory stimulation (metronome, music, clapping) to maintain timing consistency and thereby potentially facilitate spatial variability to improve curved path could be of clinical value.

Conflict of interest statement

The authors have no conflicts to report.

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